STACKING IN PROTON STORAGE RINGS WITH MISSING BUCKETS

by

W. Schnell

CERN

Geneva, Switzerland

1. Introduction

The circumference of the CERN Intersecting Storage Rings (ISR) is larger than the circumference of the injector synchrotron (CPS) by a factor 3/2. Hence, the beam, single-turn ejected from the CPS and injected into the ISR, fills only 2/3 of the ISR circumference. The filling factor becomes even smaller if two-turn injection into the ISR - or into the CPS from its booster, or both - are employed as has been proposed by Courant, Keil and Sessler[1].

In the ISR the stacking in longitudinal phase-space is done by means of an r.f. voltage that is synchronized to the bunches of protons injected from the CPS. If, as usual, the r.f. voltage is a continuous wave, some of the buckets created by the r.f. system remain empty. During each stacking cycle, the empty buckets contribute to the displacement and scatter in phase-space of previously stacked particles without adding new ones. Thus, a factor equal to the filling factor is lost in the number of protons that can be stacked within a given momentum bite. For multi-turn injection this factor is large and it has to be gained back if multi-turn injection is to be worthwhile at all. Even for single turn injection a possible improvement by a factor 3/2 is worth a certain effort.

One way of gaining back the filling factor could be to inject several CPS pulses in succession, so as to fill the entire ISR circumference before starting a new stacking cycle. However, such a scheme would entail uncomfortably close tolerances in magnetic field, frequency and phase from one CPS cycle to the next. Furthermore, additional complications would arise with the deflector magnets of two-turn injection schemes.

Another solution, and the one discussed in this paper, is to inject only once, but to suppress the empty buckets. This can be done by switching off the r.f. voltage once every particle revolution, during the time when none of the particles that have just been injected traverse the cavity. The r.f. harmonic number in the ISR is 30. Hence, if there are n bunches circulating, a missing-bucket system has to generate a chopped r.f. wave consisting of n complete sine-waves followed by (30-n) r.f. periods of zero voltage.

The obvious difficulty with this scheme is that of generating anything but a continuous sine-wave in a high-voltage, high-Q cavity. This difficulty would, indeed, be serious if it were necessary to chop the maximum peak r.f. voltage of 20 kV per turn or 3.3 kV per cavity that can be generated in the ISR. For this reason, the scheme has not been considered practicable so far.

Fortunately, however, a large voltage is required - as well as admissible - only at the beginning of the stacking cycle, when the buckets are far away from the stack (cf[2] for details of the ISR r.f. system).

Under this condition the empty buckets do little harm. Later during the stacking cycle, when the buckets approach the stack, the voltage is turned down adiabatically to the low value that corresponds to buckets fitting tightly around the bunches. Since it is only at this point that the suppression of the unwanted r.f. waves starts to become necessary a missing-bucket system seems to be feasible.

2. Required Voltage

The maximum voltage at which the r.f. cavities have to start producing a chopped wave instead of a continuous one depends strongly on the quality of the CPS beam and on ones choice of synchronous phase during stacking.

Ideally, if the beam in the CPS does not suffer any non-adiabatic blow-up of phase-oscillation amplitude from 50 MeV injection to top energy, the bunch area is so small that only about 75 V per turn - or 12.5 V per cavity - at 30° synchronous phase is required to generate tightly fitting buckets. However, the required r.f. voltage scales with the square of the bucket size so that even a moderate amount of non-adiabatic blow-up at any point of the acceleration and beam transfer processes can lead to a rather large increase in voltage. A certain amount of space-charge induced blow-up does, in fact, occur at the CPS transition energy. Several methods for compensating this blow-up have been proposed. However, at the increased intensities of an improved CPS perfect compensation may turn out to be difficult and some reserve of r.f. voltage should, therefore, be foreseen.

Furthermore, it may be considered advantageous to use larger values of synchronous phase, leading to larger voltages for given bunch-sizes, in order to make repetitive stacking schemes possible.

From both points of view an r.f. system capable of working in missing-bucket mode for a maximum voltage of about 250 V per cavity turns out to be enough to cope with all cases that could possibly arise. Even if one would fail to reach this goal by a rather large factor, the scheme is still likely to be useful.

3. Electronic problems

The most important parameter here is the electro-magnetic energy W stored in the cavity. This is conveniently expressed in terms of the quantity

$$\frac{R}{Q} = \frac{V^2}{2\omega W}$$

where V is the peak gap voltage and $\omega/2\pi$ is the r.f. frequency which is about 10 MHz in this case. For the ISR cavities presently under construction R/Q equals 16 Ω. In order to clamp the voltage at the zero crossing one has to apply a current step equal to

$$V \frac{Q}{R} .$$

When the current is switched off, the sinusoidal oscillation of the cavity continues. During the time the gap voltage is kept at zero all the stored energy remains in magnetic form.

The maximum peak current available from the normal r.f. power amplifier presently under construction is about 1.5 A. Hence, voltages of up to 24 per cavity or 144 V per turn can, in principle, be chopped by the present amplifier. As has been pointed out above, this may not be enough. In addition, the narrow bandwidth of the feedback system with which the present amplifier is equipped creates a problem.

For dealing with larger voltages a diode-chopper to be added to the cavity seems to be the best solution. For chopping as much as 250 V per cavity the diodes must be able to handle 16 A peak current and 500 V peak inverse voltage. The switching times should not exceed a few nanoseconds in order to keep the power-losses in the diodes small. This does not seem very easy at present but not likely to be impossible. During the early parts of the stacking cycle the diodes can be protected from the large r.f. voltage by means of a mechanical relay. This is possible because of the relatively slow (adiabatic) turn-down of voltage.

4. Work in progress and provisional results

Although it seems virtually certain that the average effect of a missing-bucket scheme, after a reasonably large number of stacking cycles, is much the same as if the available number of particles was evenly distributed among 30 equal buckets of correspondingly smaller size this point is going to be checked by detailed computations that have been started at CERN. No results are available as yet.

Experiments with missing buckets have been carried out at the electron storage-ring model "CESAR". Results of this are reported elsewhere at this conference.

As far as electronics is concerned, a model experiment with a very small and simple diode-switch and a resonant circuit having the same R/Q as the actual cavity has been carried out. With this circuit, a maximum of 7 V peak has been chopped. Development work on a larger chopper to be incorporated into the actual cavity has started.

REFERENCES

1. E.D. Courant, E. Keil, A.M. Sessler, contribution to this conference.

2. W. Schnell, Proc. Internat. Conf. High Energy Acc. at Dubna 1963, p. 326.